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(54) **WATERPROOF ACOUSTIC ELEMENT ENCLOSURES AND APPARATUS INCLUDING THE SAME**

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(51) **Int. Cl.**

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A61N 1/05	(2006.01)
A61N 1/36	(2006.01)

(52) **U.S. Cl.**

CPC ***H04R 25/65*** (2013.01); ***H04R 25/608*** (2013.01); *A61N 1/0541* (2013.01); *A61N 1/36032* (2013.01); *H04R 25/658* (2013.01); *H04R 2225/67* (2013.01)

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CPC H04R 2/65; H04R 2/658; H04R 1/02; H04R 1/086; H04R 1/08; H04R 1/342; H04R 1/021; H04R 1/2892; H04R 9/08; H04R 11/04; H04R 25/65; H04R 25/658; H04R 25/608; H04R 2225/67; A61N 1/36032; A61N 1/0541

USPC 381/322, 189

See application file for complete search history.

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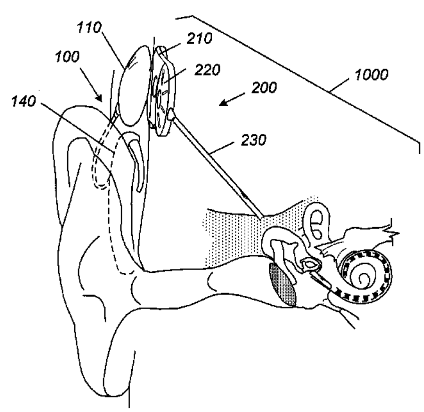
(57) **ABSTRACT**

A waterproof enclosure for a cochlear implant system or other hearing assistance device includes an outer housing, an inner support in the interior of the outer housing, an acoustic element supported by the inner support, and water-impermeable polymeric protective membrane sealing the interior of the outer housing against water ingress. A hearing device such as a cochlear implant sound processor, a headpiece, an earhook, or a hearing aid comprises an outer housing, an inner support in the interior of the outer housing, a microphone supported by the inner support, and a water-impermeable polymeric protective membrane sealing the interior of the outer housing against water ingress. A method for waterproofing an acoustic element comprises molding an outer support having a water-impermeable polymeric protective membrane; inserting an acoustic element into an inner support; anchoring the acoustic element to the inner support; inserting the inner support into the outer support; and anchoring the inner support to the outer support.

20 Claims, 6 Drawing Sheets



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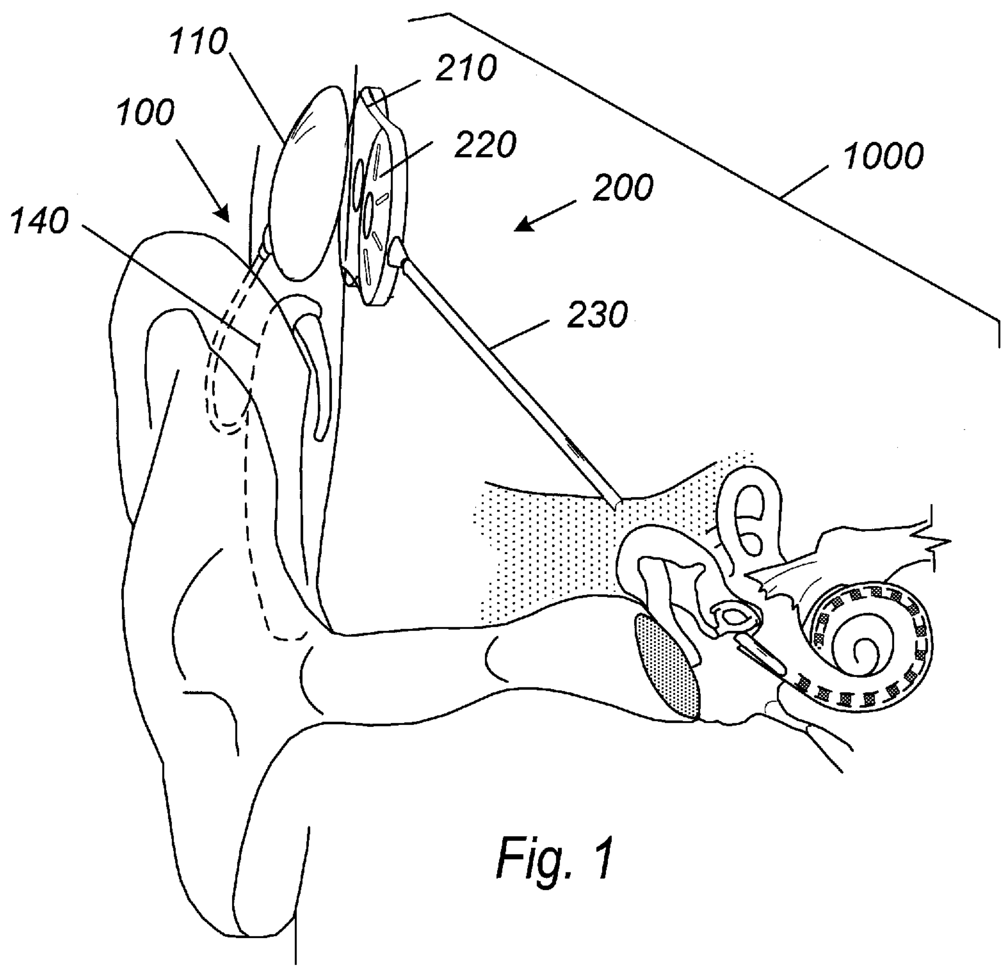

Fig. 1

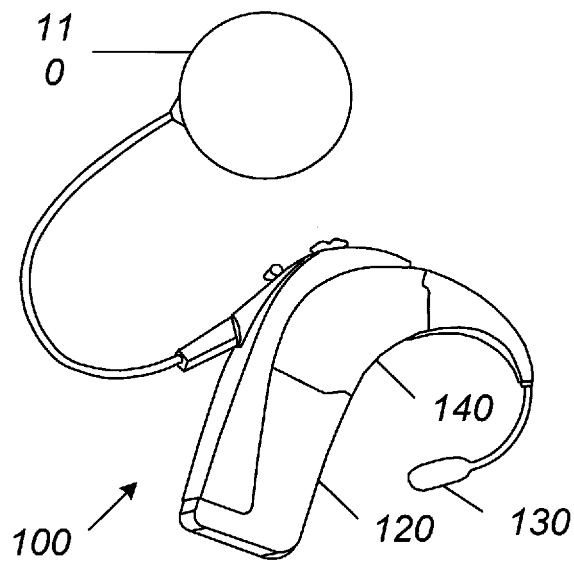

Fig. 2A

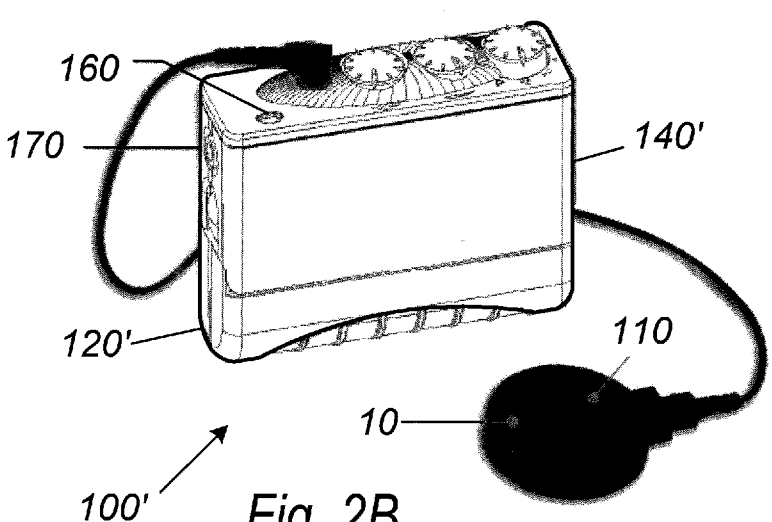

Fig. 2B

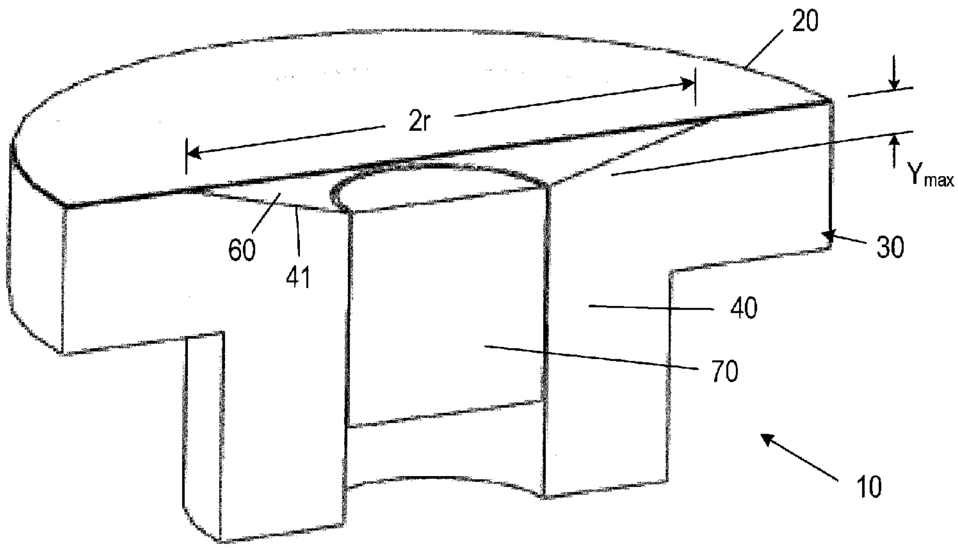

Fig. 3

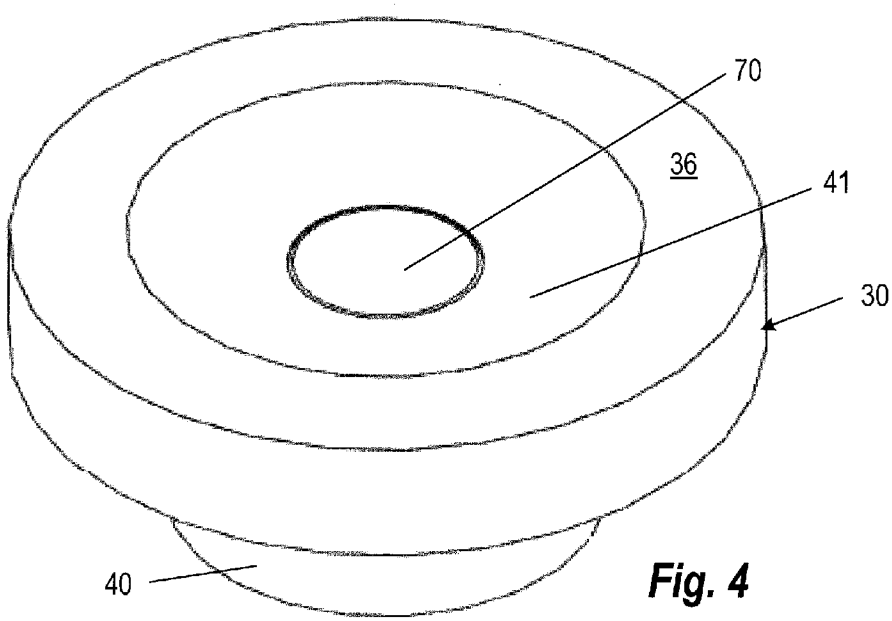

Fig. 4

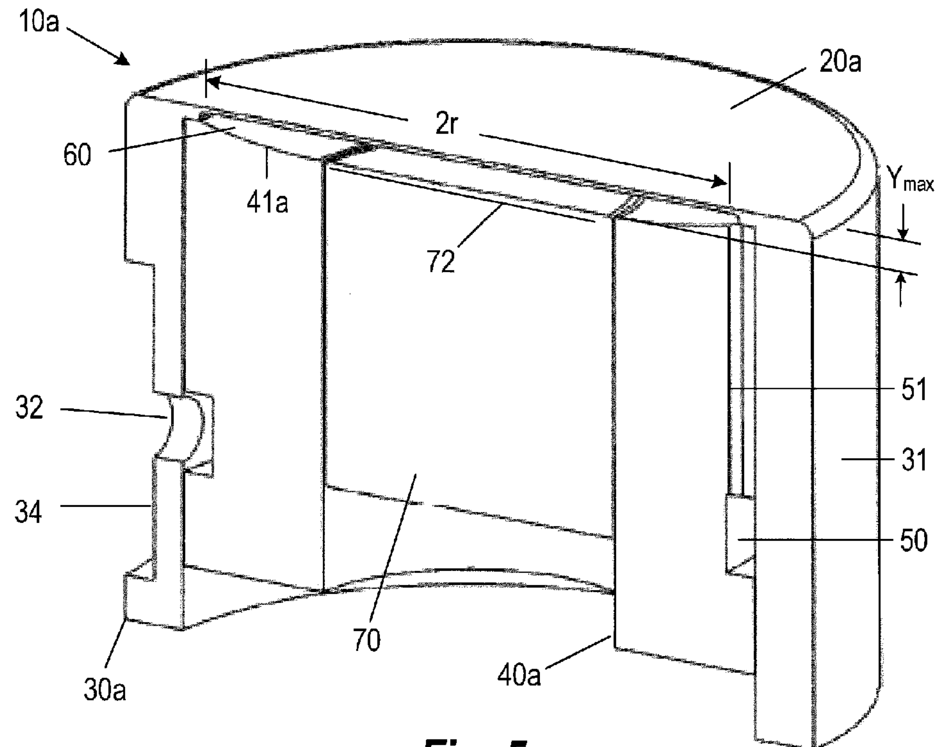
10a
20a
2r
60
41a
72
Ymax
51
32
31
34
50
70
40a
30a

Fig. 5

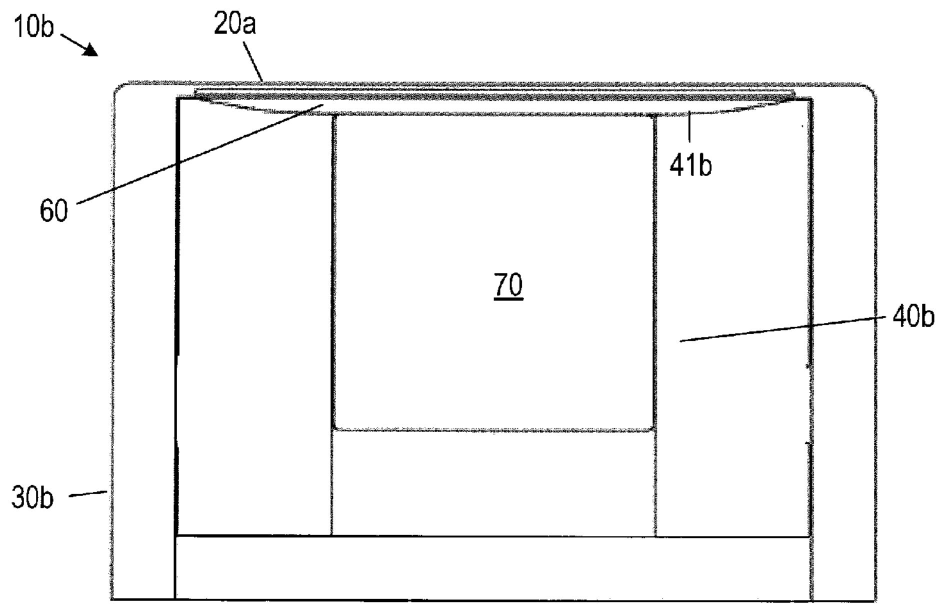
10b
20a
41b
60
70
40b
30b

Fig. 6

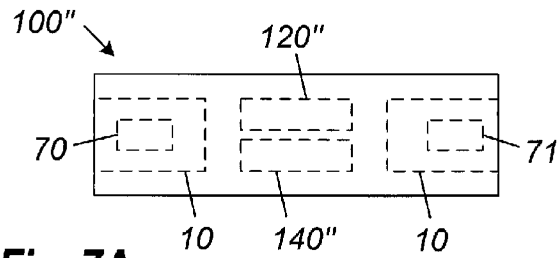

Fig. 7A

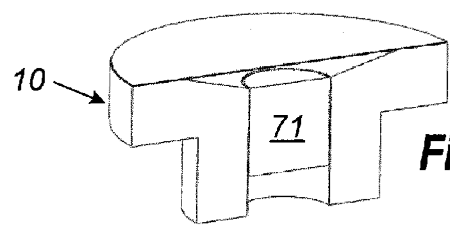

Fig. 7B

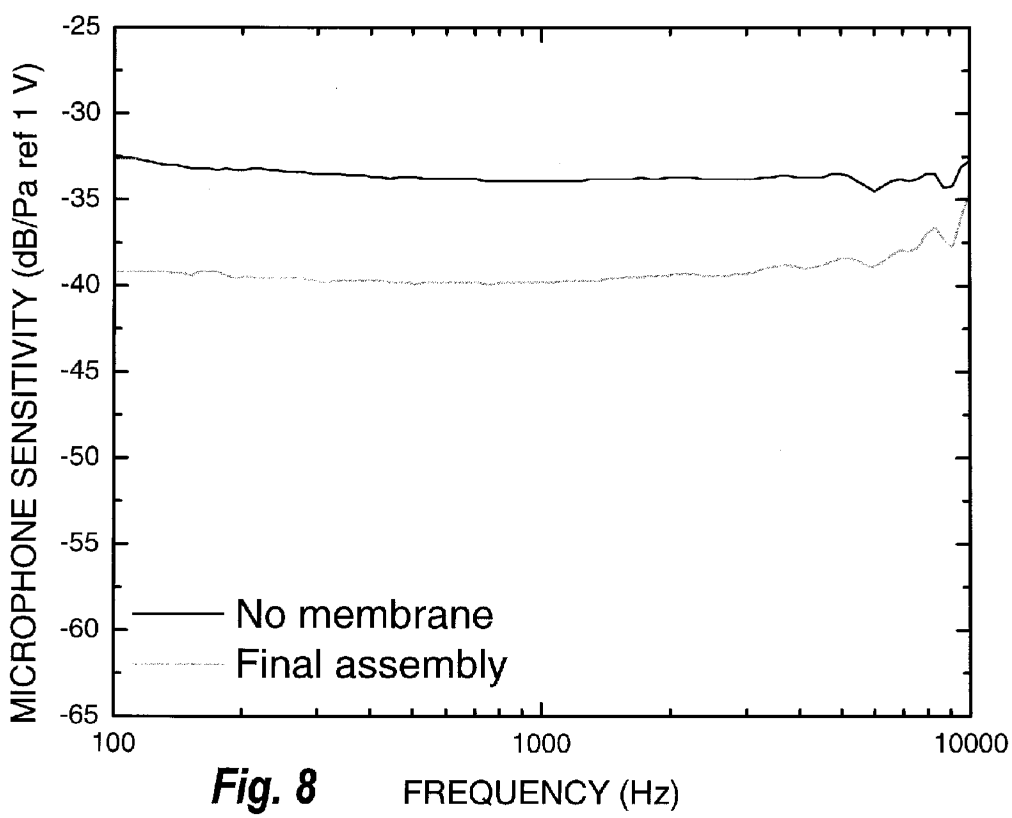

Fig. 8

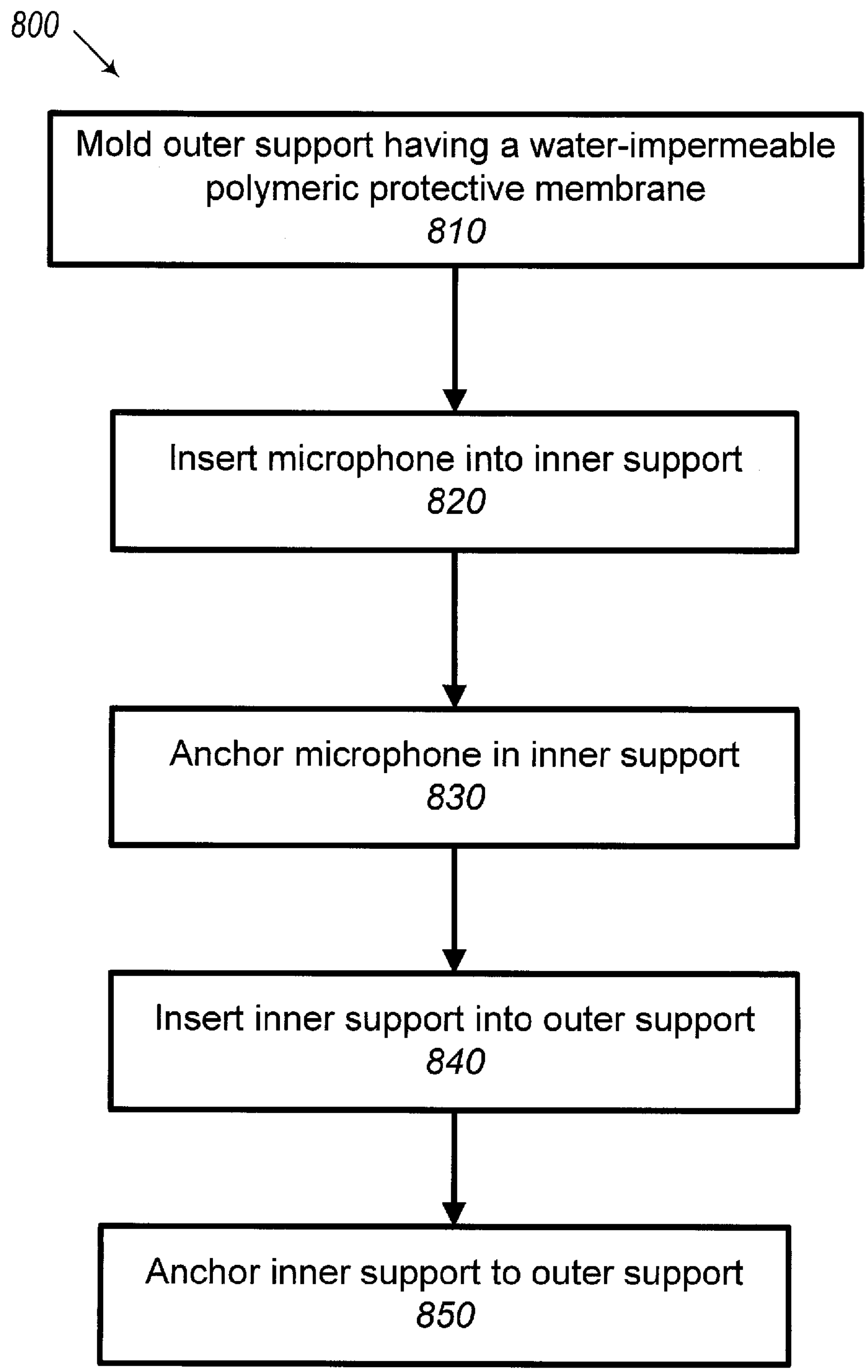
800
Mold outer support having a water-impermeable polymeric protective membrane
810
Insert microphone into inner support
820
Anchor microphone in inner support
830
Insert inner support into outer support
840
Anchor inner support to outer support
850

Fig. 9

WATERPROOF ACOUSTIC ELEMENT ENCLOSURES AND APPARATUS INCLUDING THE SAME

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation of Ser. No. 13/635,399, filed Sep. 14, 2012, now U.S. Pat. No. 8,873,783, which is the U.S. National Stage of PCT app. Ser. No. PCT/US2011/028905, filed Mar. 17, 2011, claims the benefit of U.S. Provisional Application Ser. No. 61/315,826, filed Mar. 19, 2010 and entitled "Waterproof Microphone Enclosure," each of which is incorporated herein by reference.

BACKGROUND

1. Field

The present inventions relate generally to waterproof enclosures for acoustic elements such as microphones and speakers, and may be described in the context of microphones used with a sound processor of a cochlear implant system; however, it should be understood that the inventions have application in other apparatus that include acoustic elements, such as microphones and speakers, and are exposed to moisture.

2. Description of the Related Art

Many acoustic devices are inherently sensitive to moisture and are easily damaged by water. Any apparatus that requires a microphone, speaker or other acoustic device, and needs to be water resistant or waterproof, must address this weakness. In the exemplary context sound processors and microphones, commercially-available microphones that offer protection from water are generally either too large or suffer from poor performance under the conditions that patients would like to use their sound processors. Waterproof microphones implementing sealed acoustic chambers are large and complex, and may have an undesirable frequency response, making them impractical for use with cochlear implants. Water-repellent membranes that prevent liquid water ingress but allow vapor-phase transport and have minimal impact on sound quality may be sufficient for splash-protection, but they cannot provide protection in water immersion or long-term protection from water vapor. Other problems inherent in previous designs include holes, recesses, and cavities that fill up with water and take a long time to dry. Previous designs using silicone barriers are subject to the problem that silicone absorbs water and releases it very slowly, and also that silicone tends to dampen the sound. A microphone can be sealed by dipping it in a polymer, but these designs are not feasible in a small form factor microphone, and typically suffer from poor acoustic performance.

SUMMARY

The present inventions provide acoustic element (e.g., a microphone or speaker) water protection that affords similar acoustic performance as non-waterproof acoustic elements and long-term immersion protection from liquid and vapor-phase water, and do not suffer from the shortcomings of the prior solutions. To provide an acoustic element that performs well in harsh environments, we have developed novel enclosures to make the acoustic element waterproof, using a thin film membrane material to protect the acoustic element. The present inventions also provide a method of assembling the enclosure to minimize performance variations. The membrane may be integrated with the microphone housing, and the housing may include a vent.

The present inventions solve the problems that plague current water proofing techniques for microphones and other acoustic elements. They implement a chamber that contains the acoustic element, which is completely sealed from the surrounding environment by a thin, durable, water-impermeable, polymeric protective membrane. The membrane's mechanical and physical characteristics are selected to optimize acoustic element performance in the frequency spectrum of interest for hearing devices, such as cochlear implants, hearing aids, and the like, while affording the microphone complete protection from long-term immersion and vapor-phase moisture. The mechanical structure is such that a user can clean the membrane periodically to remove any accumulated debris without damaging the membrane.

The inventions are also easily cleanable, and therefore can be kept free of cerumen (ear wax) and other debris that could potentially damage or compromise the performance of other sound pickup devices. This sealed acoustic element eliminates failures due to debris and other environmental factors, allowing patients to use their systems without worrying about environmental impact on their devices.

BRIEF DESCRIPTION OF THE DRAWINGS

The above and other aspects, features and advantages of the present inventions will be more apparent from the following more particular description thereof, presented in conjunction with the following drawings wherein:

FIG. **1** is a view of a cochlear implant system in accordance with one embodiment of a present invention;

FIG. **2**A is a view of a behind the ear sound processor in accordance with one embodiment of a present invention;

FIG. **2**B is a view of a body worn sound processor in accordance with one embodiment of a present invention;

FIG. **3** is a cross-sectional view of a microphone assembly in accordance with one embodiment of a present invention;

FIG. **4** is a top view of the microphone enclosure of FIG. **3** without the protective membrane;

FIG. **5** is a cross-sectional side view of a microphone assembly in accordance with one embodiment of a present invention;

FIG. **6** is a cross-sectional side view of a microphone assembly in accordance with one embodiment of a present invention;

FIG. **7**A is a block diagram of a hearing aid in accordance with one embodiment of a present invention;

FIG. **7**B is a cross-sectional view of a speaker assembly in accordance with one embodiment of a present invention;

FIG. **8** shows the typical frequency response of a sound processor microphone, with and without a protective membrane, respectively; and

FIG. **9** shows an exemplary production process for the production of a waterproof enclosure.

Corresponding reference characters indicate corresponding components throughout the several views of the drawings.

DETAILED DESCRIPTION OF EXEMPLARY EMBODIMENTS

The following description of the presently contemplated best modes of practicing the inventions is not to be taken in a limiting sense, but is made merely for the purpose of describing the general principles of the inventions. The scope of the inventions should be determined with reference to the claims. It should also be noted that although the present inventions are discussed below primarily in the context of microphones and cochlear implant systems, they are not so limited. By way of example, but not limitation, the present inventions have application in the context of speakers and other acoustic elements as well as in hearing aids (e.g. in-ear hearing aids) and other auditory apparatus.

One example of an acoustic element that may require protection from moisture is a microphone, and a cochlear implant system is one example of an auditory apparatus that may include a microphone and also include or embody at least some of the present inventions. To that end, FIG. **1** illustrates a cochlear implant system **1000** comprising internal components **200** and external components **100**. The internal components **200** comprise an antenna coil **210** and implanted electronics **220**, and a lead **230** having an electrode array implanted within the cochlea. The external components **100** include a headpiece **110** and sound processor **140**.

FIGS. **2**A and **2**B illustrate external components, **100** and **100'**, respectively, having behind-the-ear and body-worn sound processors, **140** and **140'**, respectively and batteries, **120** and **120'**, respectively. These processors have various controls such as sensitivity controls, volume controls, and programs switches, and may include various additional features such as a built-in LED status indicator **160** and an auxiliary port **170**. A waterproof enclosure **10** may be used to protect a microphone in any number of locations within the cochlear implant system **1000**, including the headpiece **110** (as shown in FIG. **2**B), the behind-the-ear processor **140** or body-worn sound processor **140'**, or an earhook **130** (e.g., a T-mic® in-the-ear microphone).

FIG. **3** is a cross-sectional view of a first embodiment of a waterproof enclosure, which is generally represented by reference numeral **10**, comprising a water-impermeable, polymeric protective membrane **20** mounted on an outer housing **30**. The membrane **20** is shown in an unstressed state. The waterproof enclosure **10** includes an inner support **40**, which supports a microphone **70** to define a waterproof microphone assembly. As shown in FIG. **3**, inner support **40** may be integral with outer housing **30**; alternatively, the inner support **40** may be formed by a separate component mounted within outer housing **30**, as shown and described with respect to FIGS. **5** and **6**.

FIG. **4** is a top view of the waterproof enclosure without protective membrane **20**, showing microphone **70** mounted within inner support **40**. To complete manufacturing of the waterproof enclosure **10** (FIG. **3**), protective membrane **20** would be bonded or welded to the top surface **36** of outer housing **30**, such as by pressure sensitive adhesive or ultrasonic welding. Alternatively or additionally, the protective membrane **20** may be smoothed over the top of the outer housing **30** and extend down the sides of the outer housing **30** and captured by a metallic or hard plastic hoop, which may be tightened like a drumhead. Additional adhesive may be used to bond the side walls of the outer housing **30** to the extended protective membrane **20**. In some embodiments, the adhesive used is not elastic and/or is kept thin to avoid sound dampening. For example, a pressure sensitive adhesive may be used to join the membrane **20** to the housing **30**, applying high forces to compress it; the joint thus formed may then be sealed with epoxy. As another alternative, the membrane **20** may comprise a material that can be thermally bonded to a thermoplastic or metal housing. The housing material is chosen to provide good adhesion by whichever attachment mechanism is used. As another alternative, a molded plastic outer housing **30** may be formed integral with thin protective membrane **20**, as shown and described with respect to FIGS. **5** and **6**.

FIG. **5** is a cross-sectional view of another embodiment of a waterproof enclosure, which is generally represented by reference numeral **10***a*. Waterproof enclosure **10***a* is similar to enclosure **10** and similar elements are represented by similar reference numerals. Here, however, the inner support **40***a* comprises a separate support component mounted within an outer housing **30***a*. The outer housing **30***a* may be generally cylindrical, having a curved side wall **31** that is integral with a flat end face. The flat end face forms a protective membrane **20***a*, which is shown in an unstressed state. The flat end face (i.e., protective membrane **20***a*) is very thin compared to the curved side wall **31**. This structure may be micromolded out of a polymer such as polypropylene, polyethylene terephthalate, or other material with suitable properties for the application and processing. The outer housing **30***a* has an exterior vent **32** formed therein that vents to atmosphere to enable the pressure to equilibrate inside and outside the microphone cavity. A recess **34** formed in the outer housing **30***a* provides space for a protective cover such as a mesh (not shown) that prevents particulate material from entering the vent system. A microphone **70** is mounted within inner support **40***a* within outer housing **30***a* to form a waterproof microphone assembly. The inner support **40***a* has a circumferential groove **50** and a narrow channel **51** to allow airflow through the vent **32**. The back of the assembly may be potted (not shown) to prevent water ingress.

FIG. **6** illustrates another alternative embodiment of a waterproof enclosure, which is generally represented by reference numeral **10***b* and is similar to the embodiment illustrated in FIG. **5** but without the external vent system in the outer housing. Here too, the exemplary enclosure **10***b* has a molded plastic outer housing **30***a* that is formed integral with the thin protective membrane **20***a*, which is shown in an unstressed state. The inner support **40***b* captures the microphone **70**, thereby defining a waterproof microphone assembly, and is shaped to prevent damagingly large displacements of the protective membrane caused by users pressing or rubbing the protective membrane **20***a*.

Another acoustic element that may require protection from moisture is a speaker and one example of an auditory apparatus that may include a speaker and include or embody at least some of the present inventions is an in-ear hearing aid. Turning to FIGS. **7**A and **7**B, the exemplary in-ear hearing aid **100"** includes a microphone assembly with a microphone **70** in a waterproof enclosure **10**, a battery **120"**, sound circuitry **140"**, and a speaker assembly with a speaker **71** in another waterproof enclosure **10**. In other embodiments, the enclosures **10***a* and **10***b* may be employed in conjunction with the microphone **70** and/or speaker **71**.

The protective membrane **20** (or **20***a*) protects the acoustic element against moisture but is itself exposed to the environment. Therefore, shape, structure, and materials of the enclosures **10**-**10***b* are selected such that they can be cleaned regularly without damage to the protective membrane, as is discussed in greater detail below. Because the protective membrane is exposed without a screen over it, it can be easily cleaned using a soft brush or damp towel, and there is no overlying mesh to get clogged.

The exemplary protective membrane **20** (or **20***a*) is thin, tough, flexible, and water-impermeable, and may be made out of a polymer such as liquid crystal polymer (LCP), polyester, such as polyethylene terephthalate (PET) (e.g., Mylar® PET film), polyimide (e.g., Kapton® polyimide film), or polypropylene. The polymer is chosen to be strong, puncture resistant, and thermally, chemically, and mechanically stable. The film material is also chosen to sufficiently inhibit the transport of water through the membrane such that the microphone, speaker or other acoustic element behind the membrane is not damaged. The exterior of a polymeric protective membrane **20** (or **20***a*) may be plasma treated and coated with a metallic or nonmetallic material, such as titanium dioxide, to prevent transport of water through the membrane. The coating may also prevent damage from ultraviolet (UV) radiation, make the assembly more aesthetically pleasing, and provide a substrate for a hydrophobic coating.

The membrane **20** (or **20***a*) is as thin as possible, such as less than 5 mil (0.005 inches, 0.18 mm) thick Mylar® PET film or nylon or less than 5 mil (0.005 inches, 0.18 mm) thick Kapton® polyimide film. Whether the protective membrane is integral with the outer housing (e.g., membrane **20***a*) or a separate component (e.g., membrane **20**), the protective membrane may be thinned in a secondary process, such as by laser ablation, selective dissolution, or mechanical thinning, to enhance the sensitivity of the microphone, speaker or other acoustic element inside the waterproof enclosure **10** (or **10***a* or **10***b*).

A cavity **60** is formed by the inner support **40** (or **40***a*) and protective membrane **20** (or **20***a*) and may have a geometry chosen to minimize undesirable acoustic effects, e.g., resonance. The diameter of the protective membrane **20** (or **20***a*) is large enough to ensure sufficient microphone sensitivity, while the cavity **60** has a small enough volume to suppress cavity acoustic effects (e.g., attenuation). In some embodiments, the ratio of protective membrane diameter to acoustic element membrane diameter may be 1.5 or more. The diameter of the acoustic element membrane (membrane **72** in FIG. **5**) may be approximated as being equal to the diameter of the acoustic element itself. The surface **41** (or **41***a*) of support member **40** is concave, and may be conical, parabolic, or otherwise tapered to become narrower towards the interior of the outer housing **30**. The shape of the support member surface **41** (or **41***a*) is designed to have no sharp transitions in the portion forming the wall of the cavity **60** and no sharp transition between the support member and the microphone **70**, speaker **71** or other acoustic element, thereby minimizing unwanted reflections.

The protective membrane **20** (or **20***a*) will deflect when pressed during, for example, cleaning of the protective membrane. Various attributes of the protective membrane **20** (or **20***a*) and the support member **40** (or **40***a* or **40***b*) are selected so as to prevent failure of the protective membrane. The shape of the surface **41** (or **41***a* or **41***b*) of the support member that faces the membrane, for example, is designed to have no stress concentration so as to avoid damage to the protective membrane **20** (or **20***a*). For example, the shape of the surface may be the same as the bending profile of the protective membrane under a uniform load. The membrane material, shape and dimensions, as well as the dimensions of the cavity **60**, are selected such that when external pressure is applied to the membrane during cleaning or use, the membrane will stretch but not permanently deform or tear. The membrane **20** (or **20***a*) contacts the support member surface **41** (or **41***a*) and the microphone **70**, speaker **71** or other acoustic element, which act as a stop, prior to the membrane material reaching its elastic limit (or yield stress). In other words, the distance between the protective membrane and the acoustic element must be less than the deflection distance that will result in permanent deformation or tearing of the protective membrane.

The shape, thickness and modulus of the protective membrane, as well as the distance between the protective membrane and the acoustic element, are such that stress on the protective membrane will be less than the yield stress when the protective membrane is pressed into contact with the acoustic element. Put another way, the distance between membrane and the acoustic element defines the maximum distance Y_{max} that the membrane can be deflected from its at rest state (note FIG. **3**). Distance Y_{max} is less than the deflection distance at which a membrane of a particular shape, thickness and modulus would reach its elastic limit in the absence of the stop provided by the support member surface and acoustic element.

In those instances where the protective membrane is disc-shaped, the deflection distance Y_c that will result in the membrane material reaching its elastic limit may be calculated using the following equations:

$$D1 = \frac{E \times t^3}{12 \times (1 - v^2)}$$

and

$$Y_c = \frac{q \times r^4}{64 \times D1} \times \frac{(5 + v)}{(1 + v)}$$

where

E=modulus of the membrane material,

t=membrane material thickness,

v=Poisson's ratio,

q=load/area=uniformly distributed load, and

r=membrane radius (portion that is free to deflect).

Accordingly, Y_c may be calculated for a given enclosure to determine whether or not $Y_{max}<Y_c$, as is demonstrated by the following numerical example. If the protective membrane in an acoustic element assembly is a PET film that has a modulus of 2×10^9 Pa, a thickness of 0.127 mm and a radius of 3.175 mm, that v=0.35, and that the load imparted by a finger during cleaning is 0.5 N (i.e., 63.2 KPa for the 3.175 mm radius), then Y_c=1 mm. The predicted stress under these conditions is 49.5 MPa, which is on the order of the yield stress. However, because the deflection of the membrane is constrained by the size of the cavity under the membrane, the maximum stress will be reduced relative to the free condition and the stress in the membrane will be significantly less than the yield stress. Thus, so long as Y_{max} is less than 1 mm, it may be assumed that the maximum membrane deflection permitted by the assembly will be less than that which would result in failure. Y_{max} may be further reduced, as compared to Y_c, by an appropriate safety factor (e.g. 20%).

In some embodiments, and depending on the protective membrane material type and thickness, the ratio of Y_{max} to membrane diameter will be less than 0.25, or less than 0.10, or less than 0.05, or less than 0.025.

In view of the above-described issues associated with acoustics and protective membrane preservation, the portion of the membrane that is coextensive with the cavity **60** and free to deflect in some embodiments can be, for example 0.125 to 0.300 inches (3.18 mm to 7.62 mm) in diameter, or 0.180 to 0.260 inches (4.57 mm to 6.60 mm) in diameter, or 0.250 to 0.260 (6.35 mm to 6.60 mm) inches in diameter. The distance between the protective membrane and the top of the microphone, speaker or other acoustic element can be less than 0.05 inches (1.27 mm), or on the order of 0.005 to 0.010 inches (0.13 mm to 0.25 mm), or less.

The waterproof enclosure may be combined with a variety of other waterproofing technologies to provide further waterproofing for the microphone, speaker or other acoustic element.

FIG. **8** shows a frequency response of a device with and without the protective membrane **20** of the present invention.

Typically, it is desirable that the microphone remain sensitive over a broad range of hearing frequencies, such as 100 to 8500 Hz or even 100 to 10,000 Hz. In the example shown in FIG. **8**, adding the protective membrane reduced sensitivity by less than 10 dB over the frequency range of 100 to 10,000 Hz. In this example, the housing was made of a rapid prototyping material, E shell pink photo-reactive acrylic, and the membrane was approximately 0.001 inch thick Mylar® PET film.

FIG. **9** illustrates a method **800** for making the waterproof enclosure having separately-molded inner and outer supports, **40***a* and **30***a*, respectively, such as shown in FIG. **5** or **6**. The method is described in the context of a microphone, but is also applicable to speakers and other acoustice elements. In step **810**, the outer support having a water-impermeable polymeric protective membrane is molded. The outer support may be molded onto a prefabricated film, or the film may be formed at the same time as the structural support during the molding process. In step **820**, the microphone is inserted into an inner support. In step **830**, the microphone is anchored to the inner support, such as by press fitting, adhesively bonding, or potting. This anchoring step serves to consistently define the distance between the microphone **70** and the membrane **20** (FIG. **5**). This may be done by using capture features that ensure correct microphone position and orientation. In step **840**, the inner support is inserted into the outer support. In step **850**, the inner support is anchored to the outer support, such as by an adhesive bond.

While the invention herein disclosed has been described by means of specific embodiments and applications thereof, numerous modifications and variations could be made thereto by those skilled in the art without departing from the scope of the invention set forth in the claims.

What is claimed is:

1. In a hearing assistance device selected from the group consisting of a cochlear implant sound processor, a headpiece, an earhook, and a hearing aid, the improvement comprising:

an acoustic element assembly including
- an outer housing defining an interior,
- an inner support in the interior of the outer housing,
- an acoustic element supported by the inner support, and
- a water-impermeable polymeric protective membrane that seals the interior of the outer housing against water ingress and is spaced a predetermined distance from the acoustic element when in an unstressed state, the protective membrane defining a shape, a thickness, a modulus and a yield stress,
- wherein there is a predetermined relationship between the shape, thickness and modulus of the protective membrane and the predetermined distance between the protective membrane in its unstressed state and the acoustic element, and
- wherein, as a result of the predetermined relationship, stress on the protective membrane will be less than the yield stress when the protective membrane is pressed from the unstressed state into contact with the acoustic element.

2. A hearing assistance device as claimed in claim **1**, wherein the acoustic element comprises a microphone.

3. A hearing assistance device as claimed in claim **1**, wherein the acoustic element comprises a speaker.

4. A hearing assistance device as claimed in claim **1**, wherein the inner support and outer housing are an integrally formed unit.

5. A hearing assistance device as claimed in claim **1**, wherein the inner support and the outer housing are separate structural elements.

6. A hearing assistance device as claimed in claim **1**, wherein the inner support has a tapered surface that faces the protective membrane.

7. A hearing assistance device as claimed in claim **1**, wherein the protective membrane is formed from a material selected from the group consisting of liquid crystal polymer, polyethylene terephthalate, polyester, polyimide, polypropylene and polyamide.

8. A hearing assistance device as claimed in claim **1**, wherein the protective membrane and the outer housing are an integrally formed unit.

9. A hearing assistance device as claimed in claim **1**, wherein the protective membrane and the outer housing are separate structural elements and the protective membrane is mounted on a surface of the outer housing.

10. A hearing assistance device as claimed in claim **9**, wherein the protective membrane is joined to the surface of the outer housing using an inelastic adhesive to form a joint.

11. A hearing assistance device as claimed in claim **10**, wherein the inelastic adhesive comprises a pressure sensitive adhesive.

12. A hearing assistance device as claimed in claim **10**, wherein the joint is sealed with epoxy.

13. A hearing assistance device as claimed in claim **1**, further comprising a circumferential vent between the outer housing and the inner support.

14. A hearing assistance device as claimed in claim **13**, further comprising an exterior vent formed within the outer housing in communication with the circumferential vent.

15. A hearing assistance device as claimed in claim **1**, wherein the protective membrane is not covered by a mesh structure.

16. A hearing assistance device as claimed in claim **1**, wherein the protective membrane is disc-shaped.

17. A hearing assistance device as claimed in claim **16**, wherein
- the protective membrane defines a diameter;
- the acoustic element includes a membrane defining a diameter; and
- the ratio of protective membrane diameter to acoustic element membrane diameter is 1.5 or more.

18. A hearing assistance device as claimed in claim **17**, wherein the ratio of predetermined distance to protective membrane diameter is 0.25 or less.

19. A hearing assistance device as claimed in claim **18**, wherein the protective membrane has a diameter of 0.125 to 0.300 inches (3.18 mm to 7.62 mm), and the distance between the microphone and the protective membrane is less than 0.050 inches (0.127 mm).

20. A hearing assistance device as claimed in claim **16**, wherein the predetermined distance is less than the deflection distance Y_c that will result in the protective membrane reaching its elastic limit, as calculated by the following equations:

$$D1 = \frac{E \times t^3}{12 \times (1 - v^2)}$$

and

$$Y_c = \frac{q \times r^4}{64 \times D1} \times \frac{(5 + v)}{(1 + v)}$$

where
- E=modulus of the protective membrane material,
- t=protective membrane material thickness,
- v=Poisson's ratio,
- q=uniformly distributed load, and
- r=protective membrane radius.

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